Assessing the impact made by groundwater processes and undermining on coal pit wall stability

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Abstract

Introduction. The reliability of geomechanical prediction depends on the level of detail of databases covering geological structure, geometry and physical properties of the rock mass under investigation. In order to improve the accuracy of coal pit wall stability prediction, following the generalization of databases containing geological survey, groundwater monitoring, geophysical sounding and mine surveying, it is advisable to construct three-dimensional geological-geophysical models accounting for the main adverse factors, and thereafter search for the most hazardous section.

Research aim is to predict wall stability according to the developed algorithm based on the three-dimensional geological-geophysical model.

Research methodology includes a search for the most hazardous rock mass site section by the ratio between shear and retaining forces within the established zones with anomalous physical characteristics.

Results. By generalizing databases containing geological studies, groundwater monitoring, geophysical sounding by the method of electrical resistivity tomography, and mine surveying, a three-dimensional geological-geophysical model has been constructed of a wall loaded with "heap of dry rock atop of the hydraulic dump" man-made structure and undermined by underground works. The trial site stability has been predicted for the true state of mining. Comparative analysis of the obtained data has been carried out.

Summary. The combination of natural and man-made factors, including hydrogeological conditions of the territory, seasonal and climatic behavior, tectonic faulting of the deposit and shear zones connected with undermining result in the development of a rather complex geological structure of the wall which includes local deconsolidated and waterlogged zones significantly reducing the stability of the pit slope. At the trial site of Kedrovsky pit due to spatial and temporal alternation of properties and state of rock within the landslide hazardous zone, the variation range of the factor of safety in six typical sections amounts $n = 1.06\text{--}2.39$. For that reason the objective prediction of slope stability in similar conditions (in addition to geological survey and hydrogeological observations data analysis) should include geophysical monitoring of anomalous zones origination and development, hereupon creation of a three-dimensional geological-physical model, and the automated calculation of the factor of safety including repeated selection of the most hazardous section.

Key words: man-made rock mass; groundwater; slope stability; electrical resistivity tomography; three-dimensional geological-geophysical model; factor of safety.

Introduction. The accuracy of pit slope stability prediction depends on the reliability of a geological-geophysical model which should take account of the cumulative effect of adverse factors, namely physical-geographical, engineering-geological, mining, and hydrogeological. Negative impact made by a group of physical-geographical and mining factors is predicted with a high degree of accuracy as early as at the stages of surveying and design. The reliability of assessing engineering-geological factors impact on the wall stability is conditioned by the size of a database containing physical-mechanical parameters of lithotypes, natural planes of weakness and various zones in the wall; the database grows with field development. The impact of hydrogeological factors on wall's stress state is due to, firstly, rock strength decline in water-saturated zones, secondly, hydrostatic pressure forces as a result of combined action of hydrostatic

weighing and hydrodynamic forces on the sliding wedge. Data on the condition of groundwater occurrence obtained at the stage of surveying characterize only static levels which change constantly in the course of mining. Researches [1–4] have shown that the majority of wall instability instances occur in complex hydrogeological conditions. For that reason, the problem stabilizing mine slopes when developing such deposits cannot be solved to the full extent without hydrogeological observation. Creation of classical hydroregime observation networks makes it possible to mark out aquifers within the limits of section lines; water wells interpolation of data is inevitable between the sections. In order to improve the reliability of the data it is advisable to apply geophysical methods based on electromagnetic fields application. Research done in this field have shown their effectiveness as soon as zones with anomalous humidity are sufficiently contrasting by electrical resistivity [5–11].

Table 1. Physico-mechanical properties of lithotypes and natural planes of weakness
Таблица 1. Физико-механические свойства литотипов и естественных поверхностей ослабления

Lithotype (contact of beds)	ρ , kN/m ³	C , kPa	φ , degrees
Quaternary deposits	20.1	54.0	16
Weathered original rock	22.8	153.0	33
Unweathered original rock	24.6	274.7	33
Fault zone	20.9	47.1	15
Coal	13.2	107.9	28
Aggradation rock	19.1	24.5	12
Dry spoil	18.1	14.7	32
Caving zone	19.6	0.0	31
Fractured zone	20.6	15.3	32
Contacts:			
Sandstone and siltstone	–	35.3	20
Quaternary and original rock	–	20.6	14
Coal and host rock	–	25.5	14

ρ – volumetric weight; C – cohesion; φ – angle of shear resistance.

The authors have generalized the results of studies on the groups of adverse factors in the conditions of Kedrovsky coal mine. Research aim is to predict wall stability according to the developed algorithm [12] based on the three-dimensional geological-geophysical model.

Research methodology. In order to construct three-dimensional geological-geophysical model of the wall, field survey data, geophysical research and hydrogeological observations were used.

The estimates of physical-mechanical properties of lithotypes and natural weakness planes have been obtained as a result of generalizing VNIMI research from previous years.

In order to assess water content in the wall, actual water levels have been measured in four water monitoring wells and geophysical research by the method of electrical resistivity tomography with SKALA-64 electrical exploration equipment by three profile lines 1345 m long (profile 1 is 555 m, profile 2 is 475 m, and profile 3 is 315 m). Results have been processed using specialized software to interpret electrical resistivity tomography data.

In order to determine the borders of zones with structurally weakened due to stope roof collapse, shear zone has been constructed.

Wall stability has been predicted for the actual state of mining and dumping by the method of composition of forces.

Results. The algorithm of predicting wall stability using geological-geophysical models is based on the generalization of databases covering physical-mechanical parameters of the wall, geometry of mine workings and zones with anomalous humidity. The procedure of searching for the most hazardous section contains repeated calculations of the factor of safety n for a set of vertical sections, built with the predefined linear and angular pitch [12].

Table 2. Results of measurements of actual water levels in observation wells
Таблица 2. Результаты замеров фактических уровней воды
в гидронаблюдательных скважинах

Z, m	H _{well} , m	H _{water} , m	Z _{water} , m	Test date
Well 2603				
186.0	80	56.5	129.5	March 2017
		74.2	111.8	April–May 2017
		No water	No water	June 2017
Well 2604				
165.0	65	10.7	154.3	April 2017
		30.0	135.0	May 2016
		No water	No water	June 2017
Well 2605				
195.0	74	53.4	141.6	April 2017
		68.7	126.3	May 2016
		No water	No water	June 2017
Well 2606				
121.1	67	19.5	101.6	April 2017

Z – wellhead elevation; H_{well} – well depth; H_{water} – depth of water table; Z_{water} – water table elevation.

The wall of the Kedrovsky mine under investigation represents a part of the edge within the borders of the profile lines 400–510 with heights from +120 to +195 m (abs.). The indicated geological sections analysis determined that in the site under investigation in the upper part of the geological section mainly sandstone occurs underlain by siltstone which is enclosing rock for Vladimirovsky coal bed.

Vladimirovsky roof level within the limits of geophysical profiles 1 and 2 change from +138 to +140 m (abs.). Within the limits of geophysical profile 3, Vladimirovsky roof level is +67 m (abs.). The thickness of Vladimirovsky bed within the limits of geophysical profiles is 3–4 m. Viktorovsky bed has also been discovered in the site under consideration occurring within the limits of geophysical profiles 1 and 2 near the surface. This bed is characterized by lesser thickness (0.4–0.6 m) and frequent wedging out.

The site under investigation reveals ruptures I and II discovered both within prospect lines XVIII (profile 410) and XX (profile 530).

Physical and mechanical properties of lithotypes and natural weakness planes according to VNIMI research from previous years are shown in table 1.

According to the results of groundwater survey prior to mining, groundwater in this territory have been developing at valley side slopes and tributaries of the Bolshaya Promyshlennaya, Chesnokovka and Kedrovka rivers transiting from watersheds to thalwegs where the main discharge occurred. Piezomeric surface roughly reproduced

the lay of the land. Actual hydrogeological conditions of the site are extremely complex at the present time. It is primarily conditioned by the fact that within the limits of the mine take the indicated rivers either ceased to exist or their run-off was regulated. Besides, quaternary deposits are stripped by hydromonitors, water aimed for these works is cumulated in reservoirs along the river valleys, while the pulp is discharged into the hydraulic waste disposals. A cone of depression has developed over the years of pit operation, the dimensions of which don't exceed the distance to reservoirs and hydraulic waste disposals deliberately, creating the "circulation" of groundwater and surface water in this territory.

Fig. 1. Geoelectric sections along profiles 1 – a, 2 – b and 3 – c
Рис. 1. Геоэлектрические разрезы по профилям 1 – a, 2 – b и 3 – c

It should be noted that not far from the considered site, Vladimirsky shaft mined for coal having undermined the man-made structure “heap of dry rock atop of the hydraulic dump” in the wall. The scheme shows that mine takes of the enterprises share the borderline. In section, the depth of the shaft does not exceed 100 m, for that reason the underground mines “catch” the upper part of the groundwater flow.

The following aquifers are well-presented at the territory of Kedrovsky pit:

- impervious central upper quaternary horizon (a QII-III): observations over the tributaries flowing into the pit's mine workings have shown that there are very little tributaries from loam soil;

- aquifer Lower Permian complex of the Kemerovo formation (P1 km). Lower Permian sediments within the limits of the deposits are ubiquitous. Water-bearing materials of the complex are interbedded by fractured sandstone, siltstone, argillite and coal veins. Fine-grained sandstone builds up to 60% of the quarry.

Groundwater survey in the field have shown that inundation degree of original rock is chaotic and uneven both in the scheme and in the open pit and depends on sediments displacement, lithological composition and fracture intensity, as well as on their geomorphic features. Groundwater refer to spring and autumn recharge type with a marked predominance of the former. Increase of rivers is observed during intensive

Fig. 2. Three-dimensional geologic and geophysical model of the open-pit wall – *a* and geologic sections XIX – *b*, XVIIIb – *c*, XVIIIa – *d*:
 1 – dry overburden; 2 – aggradation deposits; 3 – fractured zone; 4 – caving zone; 5 – fault; 6 – failure surface;
 7 – water table as of April 2017
 Рис. 2. Объемная геолого-геофизическая модель прибортового массива – *a* и геологические разрезы XIX – *b*, XVIIIb – *c*, XVIIIa – *d*:
 1 – породы отвала «сухой вскрыши»; 2 – намывные отложения; 3 – зона трещин; 4 – зона обрушений;
 5 – разрывное нарушение; 6 – наиболее напряженная поверхность скольжения; 7 – уровень подземных вод на 04.2017 г.

melting of snow from April till June. The shape of the piezometric surface of groundwater in virgin conditions roughly reproduced hypsographic relief, but at the present time a cone of depression has developed here over the years of pit operation. The results of actual water levels measurement in water monitoring wells are shown in table 2.

Let us consider geoelectric sections obtained after geophysical measurements interpretation. The measurements have been carried out by the method of electrical resistivity tomography of three profiles (fig. 1). It should be noted that there was no water in wells at the time of geophysical measurements.

Profile 1 was located in horizons +185...+195 m (abs.), the length of the profile was 555 m. In the initial part of the profile, at the distance of 0–30 m from the initial part, and in the upper part of the pit down to the depth of 1–5 m, a layer of piled rock with electrical resistivity less than $50 \Omega \cdot \text{m}$ has been marked out. Almost along the whole profile in the upper part of the pit down to the depth of 10–20 m, the layer of sandstone is distinguished with electrical resistivity of mainly $120\text{--}250 \Omega \cdot \text{m}$. Sites with reduced electrical resistivity in the upper part of this layer may be conditioned by intensive weathering of sandstone. At the distance of 420 m from the start of the profile in the upper part of the pit, the anomaly of reduced electrical resistivity is observed associated with well shaft 2603. Along the whole profile within the range of depths of 15–40 m, a layer with electrical resistivity $50\text{--}80 \Omega \cdot \text{m}$ is distinguished, apparently associated with the zone of clastic rock of rupture. Within this layer, at the distance of 350–400 m from the start of the profile, an area with electrical resistivity less than $50 \Omega \cdot \text{m}$ has been discovered, which may correspond to the site of high humidity in the rock mass. In the lower part of the pit at depth ranging from 35 to 55 m, a layer of siltstone with Vladimirovsky coal bed is singled out. For this bed electrical resistivity makes up mainly $270\text{--}500 \Omega \cdot \text{m}$.

Profile 2 was located in horizons +163...+173 m (abs.), profile length made up 475 m. Almost along the whole length of the profile in the upper part of the quarry down to the depth of 5–20 m a layer of sandstone is distinguished with electrical resistivity of mainly $120\text{--}200 \Omega \cdot \text{m}$. Sites with reduced electrical resistivity in the upper part of the layer are conditioned by intensive weathering of sandstone. Site with high electrical resistivity at the distance of 230–250 m from the start of the profile may be connected with Viktorovsky bed which becomes thicker here. Along the whole length of the profile at depth ranging mainly from 10 to 25 m, a layer with electrical resistivity of $50\text{--}80 \Omega \cdot \text{m}$ is distinguished, apparently associated with the zone of clastic rock of rupture. Within this layer, at the distance of 260–285 m from the start of the profile, an area with electrical resistivity less than $50 \Omega \cdot \text{m}$ has been discovered, which may correspond to the site of high humidity in the rock mass. In the lower part of the pit at depth ranging from 15 to 55 m, a layer of siltstone with Vladimirovsky coal bed is singled out. For this bed electrical resistivity makes up mainly $270\text{--}500 \Omega \cdot \text{m}$. It should be noted that towards the end of the profile the zone of clastic rock surfaces the bench.

Profile 3 was located in horizons +120...+138 m (abs.), profile length made up 315 m. In the upper part of the quarry down to the depth of 10–15 m, a layer of sandstone is distinguished with electrical resistivity of mainly $120\text{--}250 \Omega \cdot \text{m}$. At depth ranging mainly from 10 to 40 m, zones with electrical resistivity higher than $400 \Omega \cdot \text{m}$ are distinguished, apparently associated with virgin sandstone. Within this layer, zones with low electrical resistivity have been discovered, which may be connected with the zone of clastic rock of rupture. At the distance of 70–80 m, a zone with electrical resistivity less than $70 \Omega \cdot \text{m}$ has been discovered, which may correspond to the zone of higher humidity in the rock mass.

Data on the position of clastic rock in the wall obtained from the analysis of geoelectric section were accounted for when developing the three-dimensional geological-geophysical model.

Based on the constructed three-dimensional geological-geophysical model, wall's resistance against the geological quarries XIXa, XIX-1, XIX, XVIIIb, XVIIIa, XVIII was predicted. Results are presented in fig. 2 and table 3.

It has been determined from the wall stability analysis that the wall at prospecting lines XIXa, XIX-1, XIX, and XVIII is in a stable state, while at prospecting lines XVIIIa and XVIIIb it is deformed.

Table 3. The results of slope stability analysis of the open-pit wall
Таблица 3. Результаты прогноза устойчивости прибортового массива

Geological cross-section	Z_u , m	Z_l , m	h , m	α , degrees	k_1	k_2	n_1	n_2
XIXa	163.2	84.0	79.2	35	0.4	0.0	1.90	2.39
XIX-1	206.5	88.5	118.0	25	0.5	0.1	1.59	1.88
XIX	209.2	100.1	109.1	25	0.0	0.0	1.46	1.46
XVIIIb	220.0	85.4	134.6	21	0.5	0.1	1.08	1.25
XVIIIa	195.8	89.0	106.8	22	0.1	0.0	1.06	1.10
XVIII	196.1	110.0	86.1	25	0.2	0.1	1.50	1.52

Z_u/Z_l – elevations of upper and lower lips; h – height of the marginal rock mass; α – overall angle; k_1/k_2 – coefficients of inundation under maximum and minimum inundation levels; n_1/n_2 – factors and safety under inundation k_1/k_2 correspondingly.

Summary. The combination of natural and man-made factors, including hydrogeological conditions of the territory, seasonal and climatic behavior, tectonic faulting of the deposit and shear zones connected with undermining result in the development of a rather complex geological structure of the wall, which includes local deconsolidated and waterlogged zones significantly reducing the stability of the pit slope.

At the trial site of Kedrovsky pit due to spatial and temporal alternation of properties and state of rock within the landslide hazardous zone, the variation range of the factor of safety in six typical sections amounts $n = 1.06–2.39$. For that reason the objective prediction of slope stability in similar conditions (in addition to geological survey and hydrogeological observations data analysis) should include geophysical monitoring of anomalous zones origination and development, hereupon creation of a tree-dimensional geological-physical model, and the automated calculation of the factor of safety including repeated selection of the most hazardous section.

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Оценка влияния гидрогеологических процессов и подработки на устойчивость прибортового массива угольного разреза

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Реферат

Введение. Достоверность геомеханического прогноза зависит от детальности используемых баз данных о геологическом строении, геометрии и физических свойствах исследуемого массива горных пород. Для повышения точности прогноза устойчивости прибортовых массивов угольных разрезов целесообразно по результатам обобщения баз данных геологического изучения, гидрогеологического мониторинга, геофизических исследований и маркшейдерских съемок выполнять построение объемных геолого-геофизических моделей, учитывающих действие основных неблагоприятных факторов, с последующим поиском наиболее опасного сечения.

Цель работы. Прогноз устойчивости прибортового массива согласно разработанному алгоритму на основе объемной геолого-геофизической модели.

Методология. Поиск наиболее опасного сечения участка массива по соотношению сдвигающих и удерживающих сил в пределах установленных зон с аномальными физическими свойствами.

Результаты. На основе обобщения баз данных геологического изучения, гидрогеологического мониторинга, геофизических исследований методом электротомографии и маркшейдерских съемок разработана объемная геолого-геофизическая модель прибортового массива, нагруженного техногенной системой «отвал сухих пород на гидроотвале», и подработанного подземными горными работами. Выполнен прогноз устойчивости опытного участка массива для фактического положения горных работ, дан сравнительный анализ полученных результатов.

Выводы. Сочетание природных и техногенных факторов, включающих гидрогеологические условия территории, сезонный климатический режим, тектоническую нарушенность месторождения и накладываемые на нее зоны сдвижения, связанные с подработкой, приводят к формированию весьма сложной геологической структуры прибортового массива, включающей локальные разуплотненные и влагонасыщенные зоны, что существенно снижает устойчивость борта. На опытном участке разреза «Кедровский» вследствие пространственно-временных изменений свойств и состояния горных пород в пределах оползнеопасной зоны диапазон изменения коэффициента устойчивости в шести характерных сечениях составил $n = 1,06–2,39$. Поэтому объективный прогноз устойчивости борта в подобных условиях кроме анализа данных

геологических изысканий и гидрогеологических наблюдений должен включать геофизический мониторинг формирования и развития аномальных зон, создание на этой основе объемной геолого-физической модели и автоматизированный расчет коэффициента устойчивости с циклическим выбором наиболее опасного сечения.

Ключевые слова: техногенный массив; подземные воды; устойчивость откосных сооружений; электротомография; объемная геолого-геофизическая модель; коэффициент устойчивости.

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